

A New Origin of CP Revealed In A FCNC-Free Two-Higgs-Doublet Model

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Abstract

In this article, a new type of two-Higgs-doublet model will be exhibited. It not only solves the FCNC problem naturally, but also derives complex CKM-matrices. However, the CP thus derived is neither spontaneous nor explicit. It is originated in the S_3 and $S_3 + S_2$ symmetric patterns revealed in the derived mass matrices, which is a new origin of CP we never thought of. Though this model is obviously far from mature for now, it still provides us a new aspect of the nature of CP.

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I. INTRODUCTION

In the standard model (SM) of electro-weak interactions, fermions receive their masses from the nonzero vacuum expectation value (VEV) of its unique Higgs doublet through spontaneous breaking of gauge symmetries. In such a model, CP can only be put in by hands explicitly rather than be generated spontaneously through the breaking of gauge symmetries since the phase in its Higgs fields can always be rotated away, or be absorbed into its fermion fields.

In order to achieve a new origin of CP, a spontaneous one, Lee [1] extended the Higgs sector of SM with one extra Higgs doublet so that the phases may unlikely be rotated away simultaneously. In that way, he expects the phase difference between two Higgs doublets would survive and provide a spontaneous origin of CP. Unfortunately, no one has ever reached this goal so far, neither in the Higgs-potential sector nor in the Yukawa-coupling sector of the Lagrangian.

Besides the problem of the origin of CP, such an extension of SM brought about another problem, the flavor-changing neutral current (FCNC) problem. Since the mass matrix of a specific fermion type can always be divided into two components which correspond to two Higgs doublets respectively. If these two components were not diagonalized simultaneously and respectively, non-zero but cancel-each-other off-diagonal elements in each of them will induce flavor-changing neutral interactions at tree level, which is constrained tightly by experiments.

In order to evade the FCNC problem in such a two-Higgs-doublet model (2HDM), Glashow and Weinberg [2] imposed on the model a Z_2 discrete symmetry which forbids fermions to couple with both Higgs doublets simultaneously. They proposed two such models which are usually referred to as the type-I and type-II 2HDMs, or the 2HDM-I and 2HDM-II. In the 2HDM-I, one of the Higgs doublets couples with both types of quarks and the other one completely does not [3, 4]. In the 2HDM-II, one of the Higgs doublets couples only with up-type quarks and the other one only with down-type quarks [4, 5]. Besides these two models, two variations of them were proposed to include leptons. They were usually referred to as the type-X and -Y models, or the type-IV and -III models [6-10]. The type-X model is a variation of type-I as it lets one of the Higgs doublets couples only with quarks and the other one only with leptons. The type-Y model is a variation of type-II as it lets one of the Higgs doublets couples only with up-type quarks and charged leptons while the other one only with down-type quarks.

Besides these models, there is another type of 2HDM which is also referred to as the type-III 2HDM [11]. People sometimes get confused it with the one mentioned in last paragraph. However, such a model does not really solve the FCNC problem. It just sidesteps the problem by assuming the tree-level FCNCs can be suppressed down to the empirical level [12-19]. Recently, another model referred to as Aligned Two-Higgs-Doublet Model (A2HDM or ATHDM) was proposed [20], which assumes those two components of a specific mass matrix are comparative and thus eventually be diagonalized simultaneously. However, such a model won't give any CP in its Yukawa-coupling sector since the CKM matrix thus derived is always an identity matrix.

In this article, I would like to present another 2HDM which solves the FCNC problem naturally by finding pairs of matrices which can be diagonalized simultaneously. At the beginning of section II, it is just some mathematical trials to find pairs of matrices satisfying Branco's statement [21] of a naturally flavor conserving (NFC), or FCNC-free, 2HDM. Eventually, four such FCNC-free pairs are derived. One of them possesses a S_3 symmetry among three fermion generations and the other three possess extra S_2 symmetries between two of the three generations beside the S_3 symmetry. However, the readers should keep in mind that no symmetries are imposed in this article. If there were any symmetries revealed in this article, they are derived rather than imposed, even though the S_3 symmetric case in section II is completely the same as the one we derived previously in [22-24] with a presupposed S_3 symmetry. They reached the same goal by different means.

As multiple FCNC-free pairs of matrix patterns are achieved, one now has the freedom to allot different fermion types to different patterns. Eventually, the CKM matrix thus derived could be complex and CP-violating. In section III, four such complex CKM matrices will be derived. This is what the previous S_3 model in [22, 23] failed to do. Discussions and analysis regarding why CP can be derived in this model while can not in the previous S_3 model will also be given there. However, what is most interesting is the CP derived in this model is neither explicit nor spontaneous! It is originated in the specific symmetric patterns of the mass matrices rather than the phases or parameters generated spontaneously through the breaking of gauge symmetries or the phases be put in by hands explicitly in the Yukawa-coupling parameters. Finally, the study will be summarized in section IV.

II. SOLVING THE FCNC PROBLEM

In [21], Branco *et al.* presented a necessary and sufficient condition for a naturally-flavor-conserving (NFC), or FCNC-free, 2HDM as

$$M_1 M_2^\dagger - M_2 M_1^\dagger = 0, \quad (1)$$

where M_1 and M_2 are two components of a fermion mass matrix corresponding to Higgs doublets Φ_1 and Φ_2 , respectively. The type-I, -II, -X and -Y models mentioned in last section all satisfy this condition. However, they do not satisfy this condition by finding pairs of matrices which can be diagonalized simultaneously. They just sidestepped that problem by imposing a Z_2 symmetry to let one of these two components be vanish. That deservedly satisfies Eq.(1).

For example, considering only the quark sector here, the type-I and -X models assume that only one of the Higgs doublets, say Φ_1 , couples to all quark types and Φ_2 does not. That can be expressed as $M_{u2} = M_{d2} = 0$, where the sub-indices u and d indicate to which type of quarks they correspond, and it satisfies Eq.(1) obviously. For the type-II and -Y models, two Higgs doublets couple to up- and down-type quarks respectively. Thus, either $M_{u1} = M_{d2} = 0$ or $M_{d1} = M_{u2} = 0$ and both cases satisfy Eq.(1), too. In other words, these models solve the FCNC problem by forbidding fermions to couple with both Higgs doublets simultaneously.

However, people wonder if there were any 2HDM which may satisfy Eq.(1) while still preserve the freedom to couple arbitrarily fermion types to both Higgs doublets simultaneously? In [22-24], a model with a S_3 permutation symmetry among fermion generations was proposed to conform to these requirements. A pair of S_3 symmetric M_1 and M_2 which can be diagonalized simultaneously were derived there. However, that model only solved the FCNC problem while still leaved the problem of CP origin unsolved. Since only one such pair of matrices were derived there, it was applied to all fermion types and consequently the unitary transformation matrices of all fermion types are the same. Eventually, the CKM matrix derived there is always a real, 3×3 identity matrix. Of course, no CP would appear in such a model.

In what follows, totally four similar FCNC-free pairs will be derived. However, unlike the one derived in [22] with an presupposed S_3 symmetry, these FCNC-free pairs are uncovered merely through some mathematical trials to be demonstrated below. Interestingly, all of the derived pairs obviously possess a S_3 symmetry among fermion generations. One of them even has exactly the same pattern as the one derived in [22] while the other three possess extra S_2 symmetries between two of the three generations. However, the readers should keep in mind that no symmetries were presupposed in this research. If there were any symmetries appear in this article, they are derived rather than presupposed.

In order to solve the FCNC problem, one may begin with a purely mathematical trial to find pairs of matrices satisfying Eq.(1). However, the components M_1 and M_2 are obviously too complicated since there are too many unknown parameters. Thus, one has to impose some assumptions to simplify them to a manageable level.

If one assumes that both M_1 and M_2 are Hermitian conjugates of themselves, Eq.(1) will becomes

$$M_1 M_2 - M_2 M_1 = 0. \quad (2)$$

However, obviously, they are still too complicated.

If one goes one step further to assume that one of them were purely real, say M_1 , and the other one were purely imaginary, say M_2 , the most general textures of the matrices can be given as

$$M_1 = \begin{pmatrix} A_1 & B_1 & B_2 \\ B_1 & A_2 & B_3 \\ B_2 & B_3 & A_3 \end{pmatrix} = \langle \Phi_1 \rangle \begin{pmatrix} a_1 & b_1 & b_2 \\ b_1 & a_2 & b_3 \\ b_2 & b_3 & a_3 \end{pmatrix},$$

$$M_2 = i \begin{pmatrix} 0 & C_1 & C_2 \\ -C_1 & 0 & C_3 \\ -C_2 & -C_3 & 0 \end{pmatrix} = \langle \Phi_2 \rangle \begin{pmatrix} 0 & c_1 & c_2 \\ -c_1 & 0 & c_3 \\ -c_2 & -c_3 & 0 \end{pmatrix}, \quad (3)$$

where the elements A_j , B_j and C_j ($j=1, 2, 3$) are purely real and the diagonal elements of M_2 are all zero. The Yukawa coupling parameters a_j , b_j and c_j are for now still complex. But, they are to be shown all relatively real latter.

At this stage, one still has the freedom to choose phases for the VEVs of Higgs doublets. Here, I would like to choose a real $\langle\Phi_1\rangle$ to make the following derivations easier. Of course, one may choose a complex $\langle\Phi_1\rangle$ containing a phase $e^{i\theta_1}$. But, the assumption of a real M_1 would require the corresponding Yukawa-coupling matrix to contain a common factor $e^{-i\theta_1}$ which will annihilate the phase in $\langle\Phi_1\rangle$. Thus, all Yukawa-coupling parameters, a_j and b_j , in M_1 are all relatively real.

As one chooses a real $\langle\Phi_1\rangle$, then eventually $\langle\Phi_2\rangle = e^{i\theta}v_2/\sqrt{2}$, where θ is the phase difference between two VEVs. As demonstrated in [24], in a 2HDM, one needs an extra symmetry to distinguish the Higgs doublets from each other. However, such a symmetry, no matter continuous or discrete, constraints the phase difference θ to be either 0 or $\pi/2$. In what follows, the $\theta = \pi/2$ case will be shown to induce CP in the Yukawa-coupling sector.

In the $\theta = \pi/2$ case, $\langle\Phi_2\rangle = iv_2/\sqrt{2}$ is purely imaginary. Thus, all imaginary units in M_2 come solely from $\langle\Phi_2\rangle$ and all Yukawa-coupling parameters c_j are real. That means, if there were any CP thus derived, they must not be explicit!

Substituting Eq.(3) into Eq.(1), we will arrive at

$$\begin{aligned} M_2 M_1^\dagger &= i \begin{pmatrix} B_1 C_1 + B_2 C_2 & A_2 C_1 + B_3 C_2 & B_3 C_1 + A_3 C_2 \\ B_2 C_3 - A_1 C_1 & B_3 C_3 - B_1 C_1 & A_3 C_3 - B_2 C_1 \\ -A_1 C_2 - B_1 C_3 & -B_1 C_2 - A_2 C_3 & -B_2 C_2 - B_3 C_3 \end{pmatrix} \\ M_1 M_2^\dagger &= i \begin{pmatrix} -B_1 C_1 - B_2 C_2 & A_1 C_1 - B_2 C_3 & A_1 C_2 + B_1 C_3 \\ -A_2 C_1 - B_3 C_2 & B_1 C_1 - B_3 C_3 & B_1 C_2 + A_2 C_3 \\ -B_3 C_1 - A_3 C_2 & B_2 C_1 - A_3 C_3 & B_2 C_2 + B_3 C_3 \end{pmatrix}. \end{aligned} \quad (4)$$

The diagonal elements give the following equations

$$B_1 C_1 = -B_2 C_2 = B_3 C_3 \quad (5)$$

and the off-diagonal ones give another three

$$(A_1 - A_2) = (B_3 C_2 + B_2 C_3)/C_1, \quad (6)$$

$$(A_3 - A_1) = (B_1 C_3 - B_3 C_1)/C_2, \quad (7)$$

$$(A_2 - A_3) = -(B_2 C_1 + B_1 C_2)/C_3. \quad (8)$$

But, these equations are dependent since substituting Eq.(5) into the sum of Eq.(6) and Eq.(7) will arrive at Eq.(8). It is obvious that there are still infinitely many solutions for M_1 and M_2 and one needs more assumptions to reduce the number of unknown parameters.

If we assume all diagonal elements A_j are the same, i.e.,

$$A_1 = A_2 = A_3 \equiv A, \quad (9)$$

we will arrive at the following relations

$$B_1^2 = B_2^2 = B_3^2 \quad \text{and} \quad C_1^2 = C_2^2 = C_3^2. \quad (10)$$

There are four independent cases for the correlations among B_j s and C_j s. They are to be demonstrated and discussed respectively in what follows.

Case 1: $B_1 = B_2 = B_3 \equiv B$ and $C_1 = -C_2 = C_3 \equiv C$

In this case, the mass matrices can be expressed as

$$M_1 = \begin{pmatrix} A & B & B \\ B & A & B \\ B & B & A \end{pmatrix} \quad \text{and} \quad M_2 = \begin{pmatrix} 0 & iC & -iC \\ -iC & 0 & iC \\ iC & -iC & 0 \end{pmatrix}, \quad (11)$$

which are exactly the same as those derived in [22, 23] with a S_3 symmetry. However, the matrix patterns in Eq.(11) are not derived with a presupposed symmetry like what we did in [22, 23]. They are derived here by a mean very different to that.

Consequently, the mass eigenvalues can be derived as

$$(m_1, m_2, m_3) = (A - B - \sqrt{3}C, A - B + \sqrt{3}C, A + 2B) = (\alpha - \beta, \alpha + \beta, \gamma), \quad (12)$$

where $\alpha = A - B$, $\beta = \sqrt{3}C$ and $\gamma = A + 2B$ are redefined to achieve a general form for the fermion mass spectra which is to appear also in the other three cases.

The unitary transformation matrix which may diagonalize M_1 and M_2 simultaneously and respectively is derived as

$$V_1 = \begin{pmatrix} \frac{-1-i\sqrt{3}}{2\sqrt{3}} & \frac{-1+i\sqrt{3}}{2\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{-1+i\sqrt{3}}{2\sqrt{3}} & \frac{-1-i\sqrt{3}}{2\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix}, \quad (13)$$

where the sub-index k ($k=1$ to 4) of V indicates to which case it corresponds. But, the readers may have noticed that this transformation matrix is θ -independent. Even more, it is completely independent of any parameters or phases, neither the spontaneous ones nor the explicit ones. This also happens in the other three cases.

The diagonalized mass matrices can be expressed respectively as

$$V_1 M_1 V_1^\dagger = \begin{pmatrix} A - B & 0 & 0 \\ 0 & A - B & 0 \\ 0 & 0 & A + 2B \end{pmatrix}, \quad V_1 M_2 V_1^\dagger = \begin{pmatrix} -\sqrt{3}C & 0 & 0 \\ 0 & \sqrt{3}C & 0 \\ 0 & 0 & 0 \end{pmatrix}. \quad (14)$$

Obviously, it is a model free of FCNC naturally at tree level.

Case 2: $B_1 = B_2 = -B_3 \equiv B$ and $C_1 = -C_2 = -C_3 \equiv C$

In this case, the mass matrices can be expressed as

$$M_1 = \begin{pmatrix} A & B & B \\ B & A & -B \\ B & -B & A \end{pmatrix}, \quad M_2 = \begin{pmatrix} 0 & iC & -iC \\ -iC & 0 & -iC \\ iC & iC & 0 \end{pmatrix}. \quad (15)$$

The mass eigenvalues can be derived as

$$(m_1, m_2, m_3) = (A + B - \sqrt{3}C, A + B + \sqrt{3}C, A - 2B) = (\alpha - \beta, \alpha + \beta, \gamma), \quad (16)$$

where $\alpha = A + B$, $\beta = \sqrt{3}C$ and $\gamma = A - 2B$ were redefined to have the same texture as Eq.(11).

The corresponding transformation matrix can be given as

$$V_2 = \begin{pmatrix} \frac{1-i\sqrt{3}}{2\sqrt{3}} & \frac{-1-i\sqrt{3}}{2\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1+i\sqrt{3}}{2\sqrt{3}} & \frac{-1+i\sqrt{3}}{2\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix}. \quad (17)$$

However, if we reformulate Eq.(15) as

$$M_1 = \begin{pmatrix} A & B & B \\ B & A & B \\ B & B & A \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -2B \\ 0 & -2B & 0 \end{pmatrix}, \quad M_2 = \begin{pmatrix} 0 & iC & -iC \\ -iC & 0 & iC \\ iC & -iC & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -2iC \\ 0 & 2iC & 0 \end{pmatrix} \quad (18)$$

It is obvious that the first parts of both matrices are exactly the same as those in Eq.(11) which possess a S_3 symmetry, while the second parts of them obviously reveal an extra S_2 symmetry among the second and third generations. As to be shown in next section, these extra S_2 symmetries are the keys to derive complex CKM matrices.

Case 3: $B_1 = -B_2 = B_3 \equiv B$ and $C_1 = C_2 = C_3 \equiv C$

In this case, the mass matrices can be expressed as

$$M_1 = \begin{pmatrix} A & B & -B \\ B & A & B \\ -B & B & A \end{pmatrix}, \quad M_2 = \begin{pmatrix} 0 & iC & iC \\ -iC & 0 & iC \\ -iC & -iC & 0 \end{pmatrix}. \quad (19)$$

The mass eigenvalues can be given as

$$(m_1, m_2, m_3) = (A + B - \sqrt{3}C, A + B + \sqrt{3}C, A - 2B) = (\alpha - \beta, \alpha + \beta, \gamma), \quad (20)$$

where the elements of its mass eigenvalues were redefined as $\alpha = A + B$, $\beta = \sqrt{3}C$ and $\gamma = A - 2B$.

The corresponding transformation matrix can be derived as

$$V_3 = \begin{pmatrix} \frac{-1+i\sqrt{3}}{2\sqrt{3}} & \frac{1+i\sqrt{3}}{2\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{-1-i\sqrt{3}}{2\sqrt{3}} & \frac{1-i\sqrt{3}}{2\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix}. \quad (21)$$

In this case, just like what happened in case 2, the mass matrices can also be divided into one S_3 -symmetric and one S_2 -symmetric parts respectively.

$$M_1 = \begin{pmatrix} A & B & B \\ B & A & B \\ B & B & A \end{pmatrix} + \begin{pmatrix} 0 & 0 & -2B \\ 0 & 0 & 0 \\ -2B & 0 & 0 \end{pmatrix}, \quad M_2 = \begin{pmatrix} 0 & iC & -iC \\ -iC & 0 & iC \\ iC & -iC & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 2iC \\ 0 & 0 & 0 \\ -2iC & 0 & 0 \end{pmatrix} \quad (22)$$

The extra S_2 symmetry appears between the first and third generations.

Case 4: $B_1 = -B_2 = -B_3 \equiv -B$ and $C_1 = C_2 = -C_3 \equiv -C$

In this case, the mass matrices can be expressed as:

$$M_1 = \begin{pmatrix} A & -B & B \\ -B & A & B \\ B & B & A \end{pmatrix}, \quad M_2 = \begin{pmatrix} 0 & -iC & -iC \\ iC & 0 & iC \\ iC & -iC & 0 \end{pmatrix}. \quad (23)$$

The mass eigenvalues thus derived are

$$(m_1, m_2, m_3) = (A + B - \sqrt{3}C, A + B + \sqrt{3}C, A - 2B) = (\alpha - \beta, \alpha + \beta, \gamma), \quad (24)$$

where the mass eigenvalues were redefined as $\alpha = A + B$, $\beta = \sqrt{3}C$ and $\gamma = A - 2B$.

The corresponding transformation matrix can be derived as

$$V_4 = \begin{pmatrix} \frac{1-i\sqrt{3}}{2\sqrt{3}} & \frac{1+i\sqrt{3}}{2\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1+i\sqrt{3}}{2\sqrt{3}} & \frac{1-i\sqrt{3}}{2\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix}. \quad (25)$$

In this case, the mass matrices can also be divided into one S_3 -symmetric and one S_2 -symmetric parts respectively.

$$M_1 = \begin{pmatrix} A & B & B \\ B & A & B \\ B & B & A \end{pmatrix} + \begin{pmatrix} 0 & -2B & 0 \\ -2B & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad M_2 = \begin{pmatrix} 0 & iC & -iC \\ -iC & 0 & iC \\ iC & -iC & 0 \end{pmatrix} + \begin{pmatrix} 0 & -2iC & 0 \\ 2iC & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (26)$$

The extra S_2 symmetry appears here is between the first and second generations.

It is interesting that the mass matrices derived in cases 2, 3 and 4 not only possess a S_3 permutation symmetry among three fermion generations. They also reveal extra S_2 symmetries between two of the three generations. In other words, they all possess a S_3+S_2 texture except for between which two generations the S_2 symmetries apply.

Besides, since in each of these four cases the matrices M_1 and M_2 can be diagonalized simultaneously, arbitrary hybrids of them will also be diagonalized by the same corresponding V_k . Thus, the mass matrices can be complex and the assumption of a purely real M_1 and a purely imaginary M_2 at the beginning of this section is not indeed necessary. However, it is still very useful during the derivation of the matrix patterns.

It is more interesting that the unitary transformations of all four cases are completely independent of any phases or parameters in the model. Thus, if there were any CP derived in such a model, it must not be spontaneous. Besides, since all elements of the Yukawa-couplings are relatively real as proved at the beginning of this section and their common phases can always be rotated away. If there were any CP derived, it must not be explicit neither. The derivation of such a neither spontaneous nor explicit origin of CP will be given in the next section.

III. A NEITHER SPONTANEOUS NOR EXPLICIT ORIGIN OF CP

In a 2HDM, CP is likely to be violated in two sectors of its Lagrangian, one is the Higgs potential sector and the other is the Yukawa-coupling sector. In what follows, it is to be demonstrated that the FCNC-free textures derived in last section can also derive CP-violating CKM matrices in the Yukawa-coupling sector. Interestingly, the CP thus derived are neither spontaneous nor explicit. They are originated in a completely different origin we never thought of, the symmetric pattern of the mass matrices.

If one reviews the S_3 model in [22, 23], he may find the major cause of its failure to give a CP-violating CKM-matrix is: there was only one such FCNC-free pair of matrices for all fermion types! In that case, $V^u = V^d$ makes the CKM matrix always an identity matrix, i.e., $V_{CKM} = V^u V^{d\dagger} = 1_{3\times 3}$. Thinking contrarily, $V^u \neq V^d$ is a necessary but not sufficient condition for deriving a CP-violating CKM matrix. Besides, at least one of the transformation matrices must be complex, or the CKM matrix will be purely real and CP-conserving.

As derived in last section, we have now totally four such pairs for the mass matrices. Thus, different fermion types can be allotted to different patterns so as to satisfy the condition mentioned in last paragraph. Various CKM-matrices thus derived are tabulated as in TABLE I.

The diagonal elements of TABLE I are all the same and $1_{3\times 3}$ indicates a 3×3 identity matrix. The hyper-index "*" means the complex conjugate. The details of the matrices

| V_{CKM} | $V_1^{d\dagger}$ | $V_2^{d\dagger}$ | $V_3^{d\dagger}$ | $V_4^{d\dagger}$ |
|-----------|------------------|------------------|------------------|------------------|
| V_1^u | $1_{3\times 3}$ | D | D^* | F |
| V_2^u | D^* | $1_{3\times 3}$ | G | E |
| V_3^u | D | G | $1_{3\times 3}$ | E^* |
| V_4^u | F | E | E^* | $1_{3\times 3}$ |

TABLE I: Various assemblies of CKM-matrix.

D , E , F and G are given as what follows

$$\begin{aligned}
D &= \begin{pmatrix} \frac{1-i\sqrt{3}}{3} & \frac{1}{3} & \frac{1+i\sqrt{3}}{3} \\ \frac{1}{3} & \frac{1+i\sqrt{3}}{3} & \frac{1-i\sqrt{3}}{3} \\ \frac{1+i\sqrt{3}}{3} & \frac{1-i\sqrt{3}}{3} & \frac{1}{3} \end{pmatrix}, \quad E = \begin{pmatrix} \frac{1}{3} & \frac{1-i\sqrt{3}}{3} & \frac{1+i\sqrt{3}}{3} \\ \frac{1+i\sqrt{3}}{3} & \frac{1}{3} & \frac{1-i\sqrt{3}}{3} \\ \frac{1-i\sqrt{3}}{3} & \frac{1+i\sqrt{3}}{3} & \frac{1}{3} \end{pmatrix}, \\
F &= \begin{pmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{2}{3} \\ \frac{-1}{3} & \frac{2}{3} & \frac{2}{3} \\ \frac{2}{3} & \frac{2}{3} & \frac{-1}{3} \end{pmatrix}, \quad G = \begin{pmatrix} \frac{-1}{3} & \frac{2}{3} & \frac{2}{3} \\ \frac{2}{3} & \frac{-1}{3} & \frac{2}{3} \\ \frac{2}{3} & \frac{2}{3} & \frac{-1}{3} \end{pmatrix}.
\end{aligned} \tag{27}$$

The matrices $1_{3\times 3}$, F and G are purely real and obviously CP-conserving. While D , E and their complex conjugates are complex, CP-violating. However, the CP thus derived is completely independent of θ or any parameters in the model. Thus, it is neither spontaneous nor explicit!

Though the FCNC-free model discussed above provided a mechanism to induce CP-violation in the Yukawa-coupling sector successfully. However, the model is still far from mature since the magnitudes of the derived CKM-matrix elements do not fit the empirical values well. If one expresses the matrices D and E as

$$D = \begin{pmatrix} \frac{2}{3}e^{-i\frac{\pi}{6}} & \frac{1}{3} & \frac{2}{3}e^{i\frac{\pi}{6}} \\ \frac{1}{3} & \frac{2}{3}e^{i\frac{\pi}{6}} & \frac{2}{3}e^{-i\frac{\pi}{6}} \\ \frac{2}{3}e^{i\frac{\pi}{6}} & \frac{2}{3}e^{-i\frac{\pi}{6}} & \frac{1}{3} \end{pmatrix}, \quad E = \begin{pmatrix} \frac{1}{3} & \frac{2}{3}e^{-i\frac{\pi}{6}} & \frac{2}{3}e^{i\frac{\pi}{6}} \\ \frac{2}{3}e^{i\frac{\pi}{6}} & \frac{1}{3} & \frac{2}{3}e^{-i\frac{\pi}{6}} \\ \frac{2}{3}e^{-i\frac{\pi}{6}} & \frac{2}{3}e^{i\frac{\pi}{6}} & \frac{1}{3} \end{pmatrix}, \tag{28}$$

it is trivial that both of them differ from the empirical values given in [26] very much. Obviously, the textures of the matrices derived above are still too brief. The real textures of nature must be much more complicated than those derived here. However, the model still hints us a very new aspect of the nature of CP.

IV. CONCLUSIONS

In this article, a new origin of CP is presented and discussed. The study began with an effort trying to find FCNC-free pairs of mass matrices satisfying Branco's statement. It was

proved that such FCNC-free pairs of mass matrices do exist and the way how such pairs were derived was also demonstrated. However, multiple such FCNC-free pairs were found. That enables us to derive several complex CKM-matrices. It is interesting that the CP thus derived is neither spontaneous nor explicit. The origin of CP in such a model is the specific symmetric pattern of the mass matrices. Though the patterns of the derived FCNC-free pairs of mass matrices obviously revealed some S_3 or $S_3 + S_2$ symmetric textures, these symmetries are not presupposed like what was done in [22, 23]. They were derived by very different means.

Obviously, the FCNC-free model presented in this article is still far from mature. The magnitudes of the derived CKM matrix elements do not fit the empirical values very well. Which means one may need some more complicated patterns to achieve a better fitted CKM matrix. However, theoretically, there must be many more such FCNC-free pairs except the four derived in this article. In fact, there are infinitely many of them. The only question is how to find some more feasible and definite textures than those derived in this article. That will be a long, hard way to go. However, the research in this article has hinted us a new aspect to study the origin of CP.

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